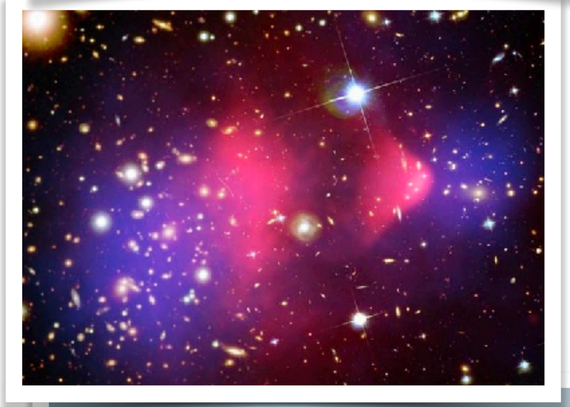
The future Neutrino Program from a Theory Perspective

Pedro Machado

March 21st, 2023

Closed caption box

The outstanding questions in neutrino physics and beyond, guided by neutrino experiments



The mechanism of neutrino masses
The nature of neutrinos
The unification of all forces
The matter-antimatter asymmetry
Neutrinos as a portal to new physics
CP violation in the leptonic sector
The absolute masses of neutrinos
Neutrino mixings: patterns and symmetries
Existence of extra neutrino species

The nature of dark matter
CP violation in strong interactions
The existence of dark sectors

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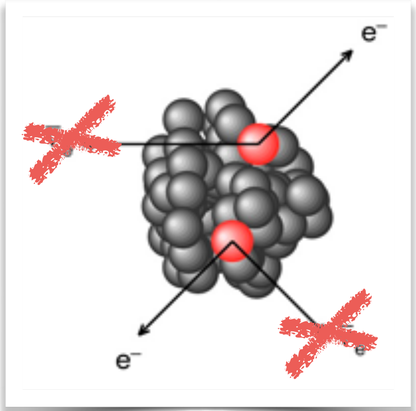

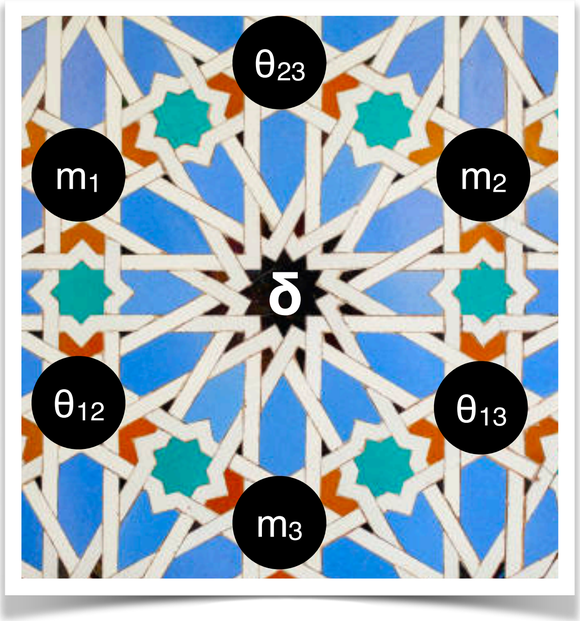

Where does the standard model break?

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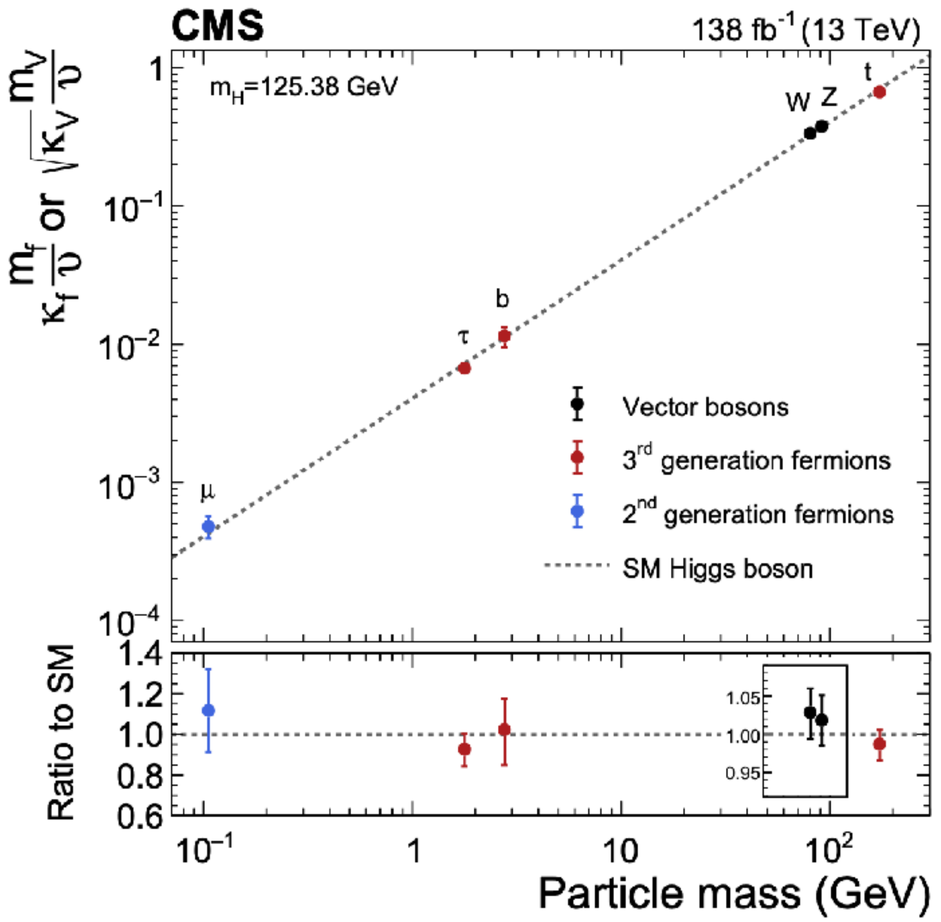
The mechanism of neutrino masses

The mechanism of neutrino masses is qualitatively different from charged fermions

All particles within the framework of the standard model, except for neutrinos, get their masses directly and exclusively from the Higgs mechanism

Data points in that direction, at least for charged fermions of the 2nd and 3rd families and gauge bosons

But neutrinos are very different



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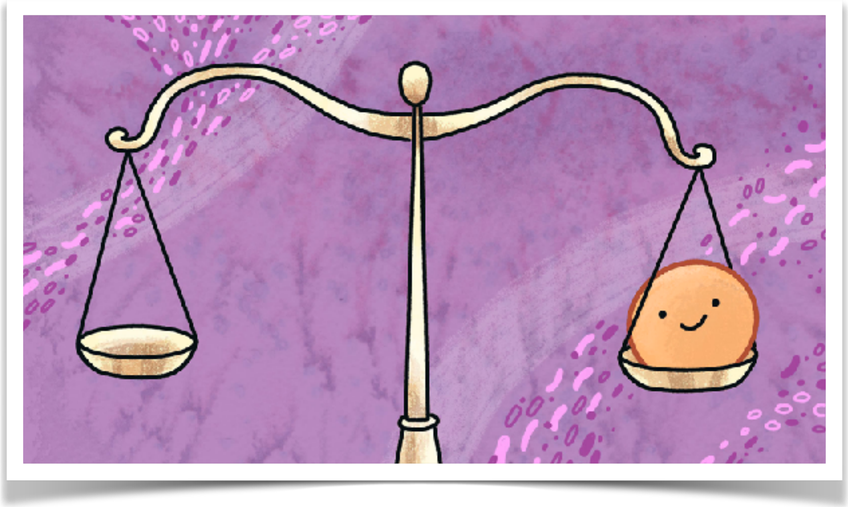
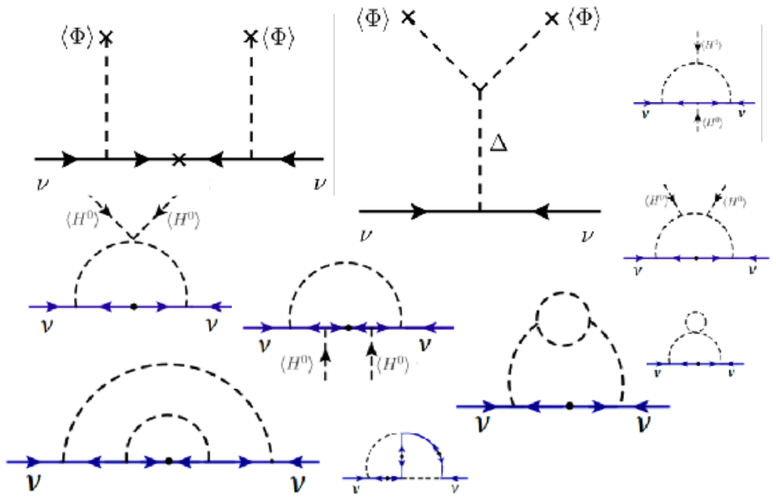
The mechanism of neutrino masses

Just repeating the Higgs mechanism for neutrinos (invoking a right-handed neutrino) would **predict a particle that is completely different from all observed particles**: its mass has nothing to do with electroweak symmetry breaking

Possible realizations of the neutrino mass mechanism span at least 20 orders of magnitude in scale, from the sub-eV to grand unification, and there is little to no experimental guidance on the right energy scale

Similar to the theory landscape in dark matter physics





Miranda Valle 1602.00864
Babu et al 1907.09498

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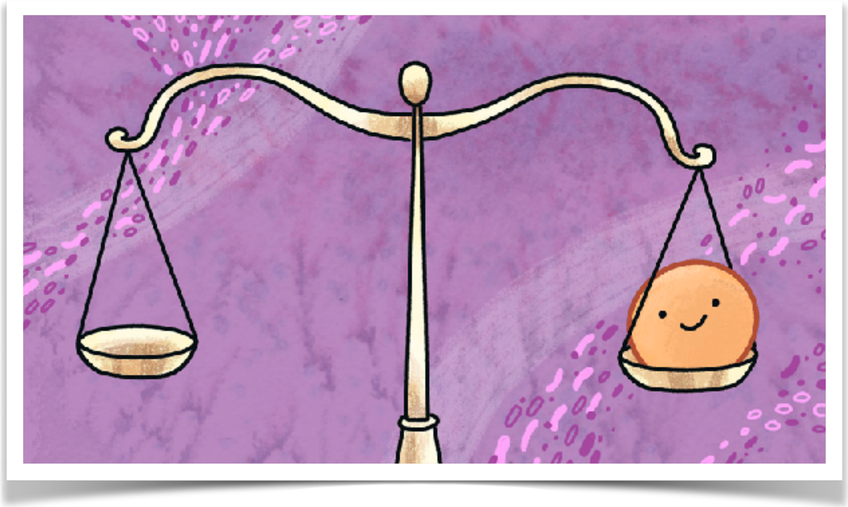
The mechanism of neutrino masses

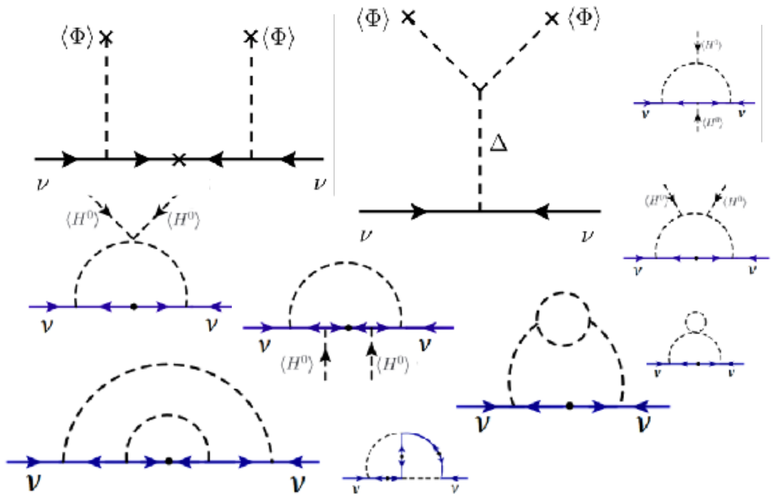
One key point:
The neutrino mass mechanism is much more than neutrino masses,
just as electroweak symmetry breaking is much more than the Fermi constant

Of course, we need to determine neutrino masses and the nature of neutrinos, but it is crucial that we go beyond these measurements

We need to approach the problem from many sides

We need a precision neutrino physics program





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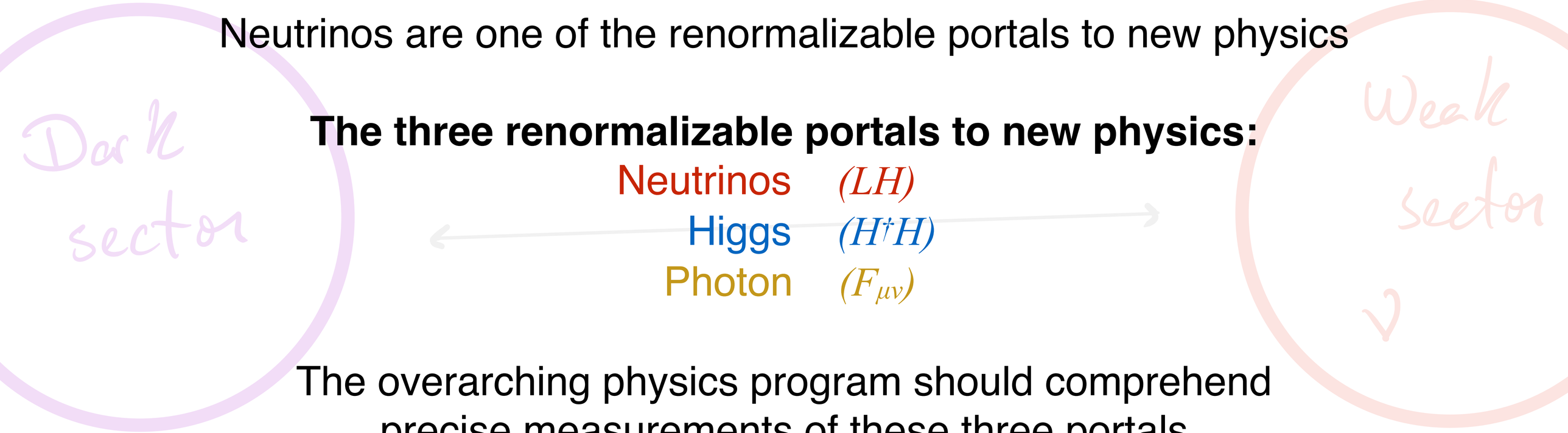
Exploring the unknown through the lens of neutrinos

From a theory perspective, (LH) is special: it is a gauge-singlet

Neutrinos are one of the renormalizable portals to new physics



The three renormalizable portals to new physics:

Neutrinos (LH)

Higgs $(H^\dagger H)$

Photon $(F_{\mu\nu})$

The overarching physics program should comprehend precise measurements of these three portals

We need a precision neutrino physics program

Marshall's talk

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Precision physics program

Measure same parameters with different observables

Test predictions of the model, given previous measurements

Example:

M_Z at LEP with good precision is great,

but the model is really tested when we e.g. measure the *weak mixing angle*

and compare with the prediction given M_Z and M_W measurements

Currently, the closest we get to a precision neutrino physics program is encoded in the measurements of δ_{cp} and the atmospheric mixing angle

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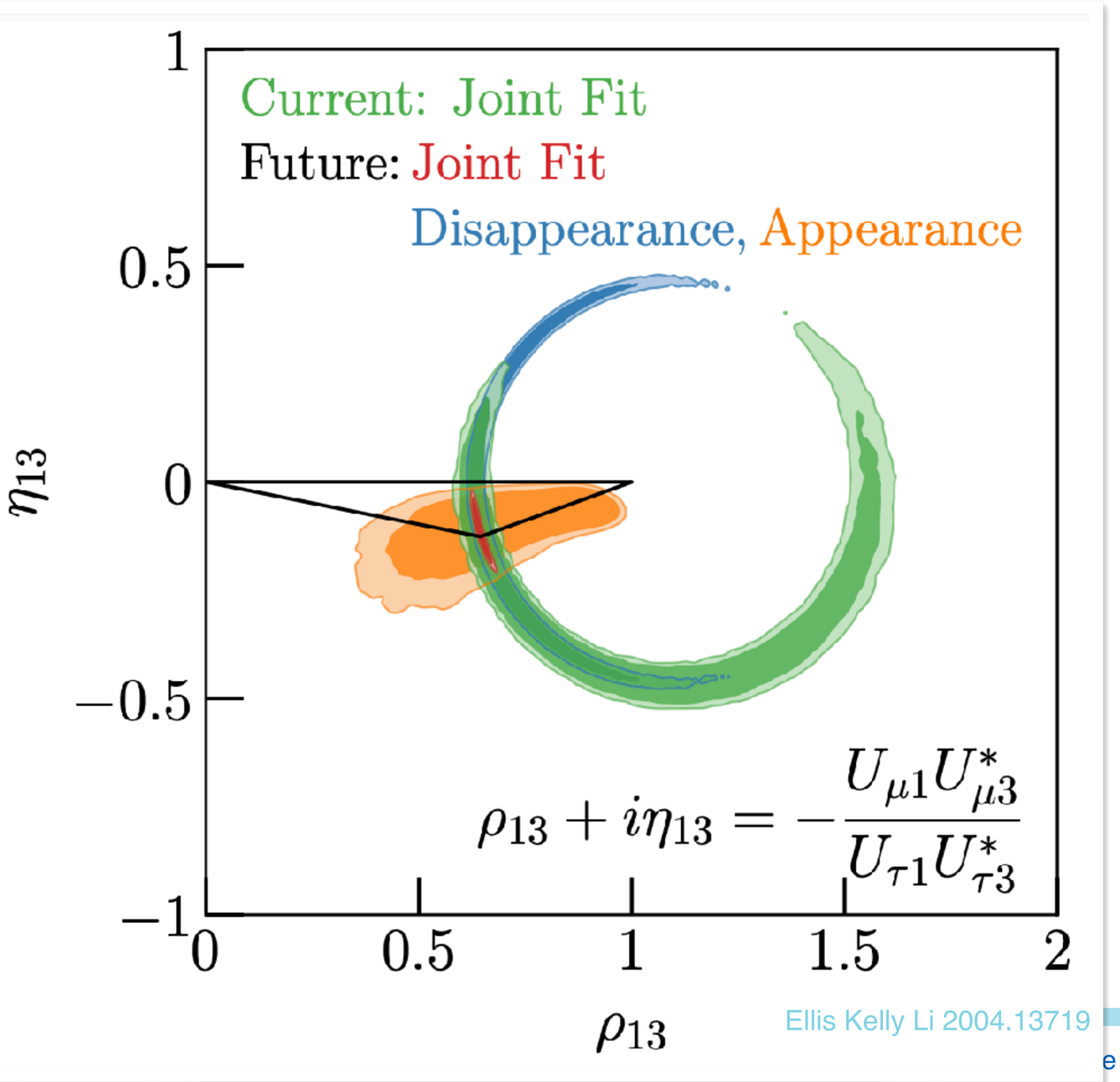
Exploring the unknown through the lens of neutrinos



Ellis Kelly Li 2004.13719

DUNE, HK, JUNO and IceCube will enable a bona fide precision physics program in the neutrino sector

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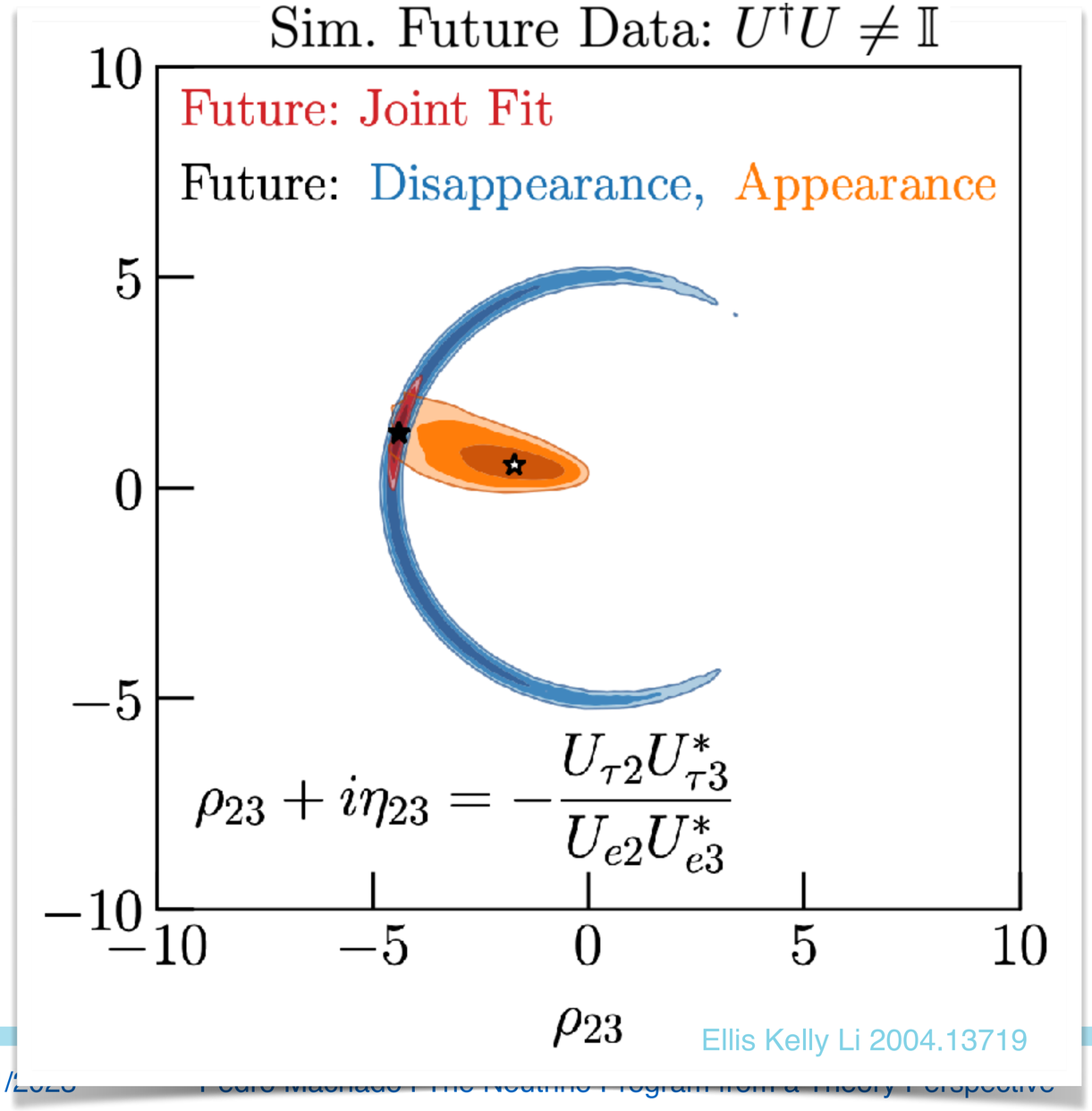
Exploring the unknown through the lens of neutrinos



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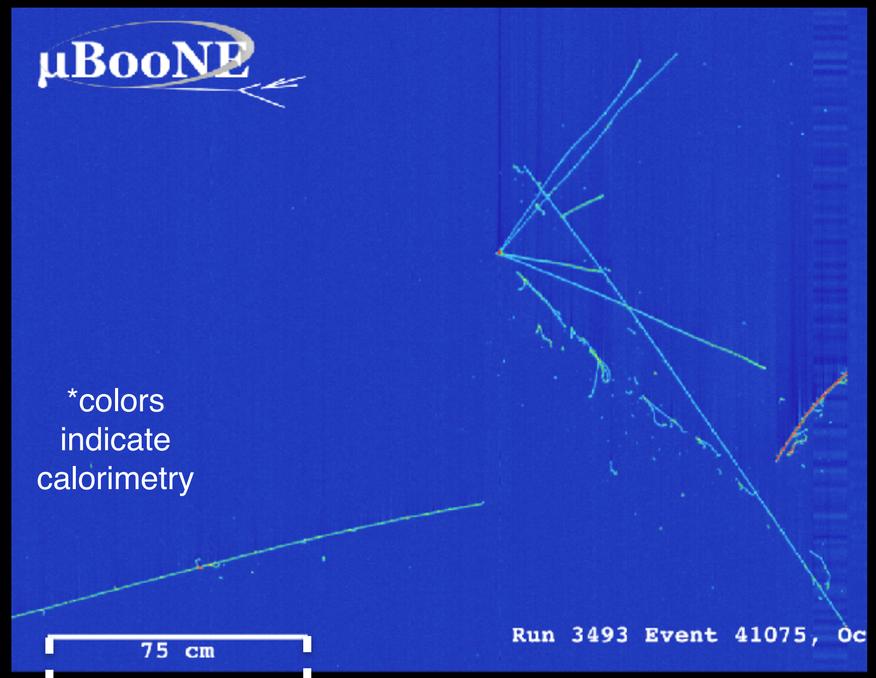


event
displays
to scale

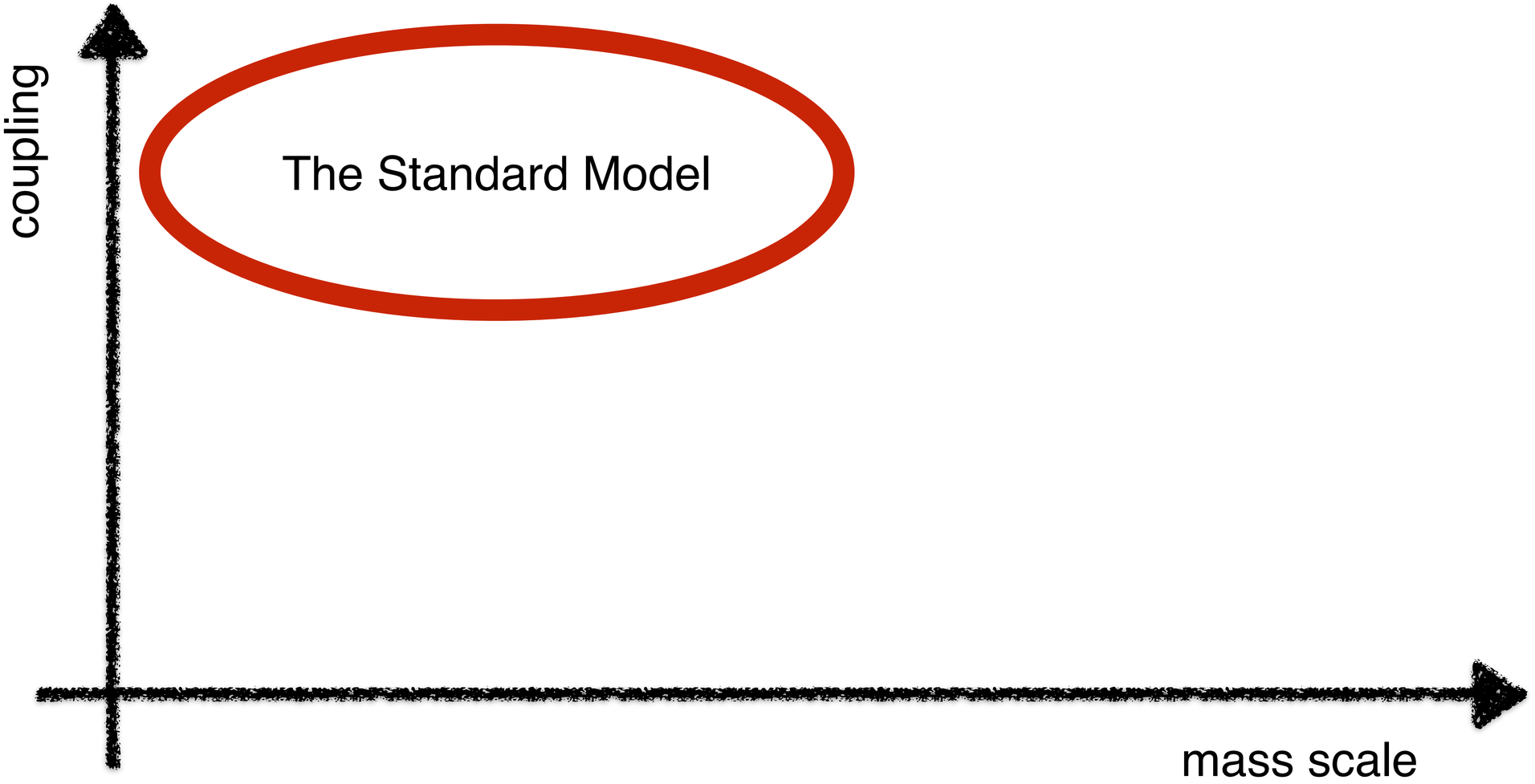
New technologies are transformative

Neutrino experiments are multipurpose

Neutrino experiments offer unique probes of new physics

NOvA

How do neutrino experiments help probing new physics?



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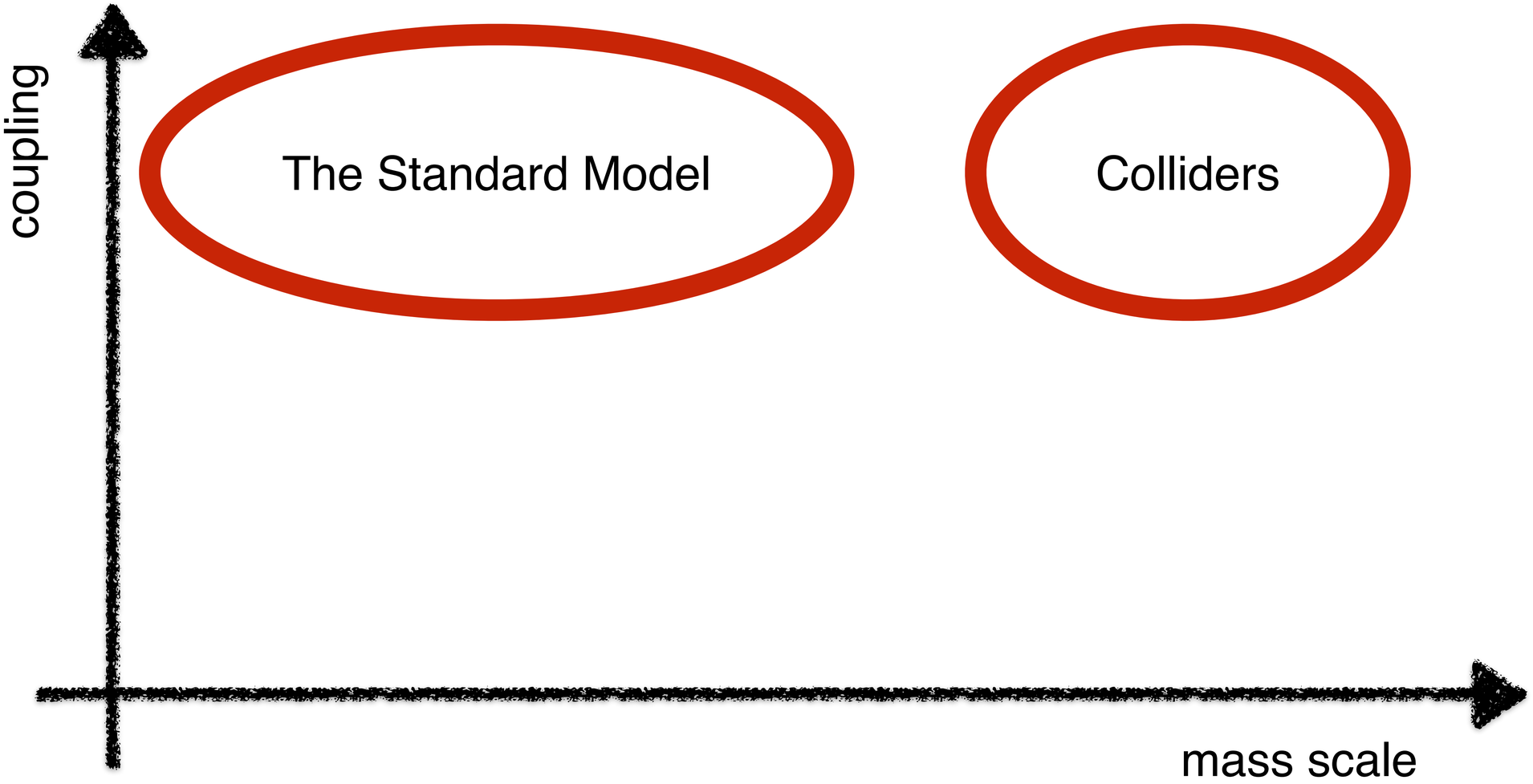

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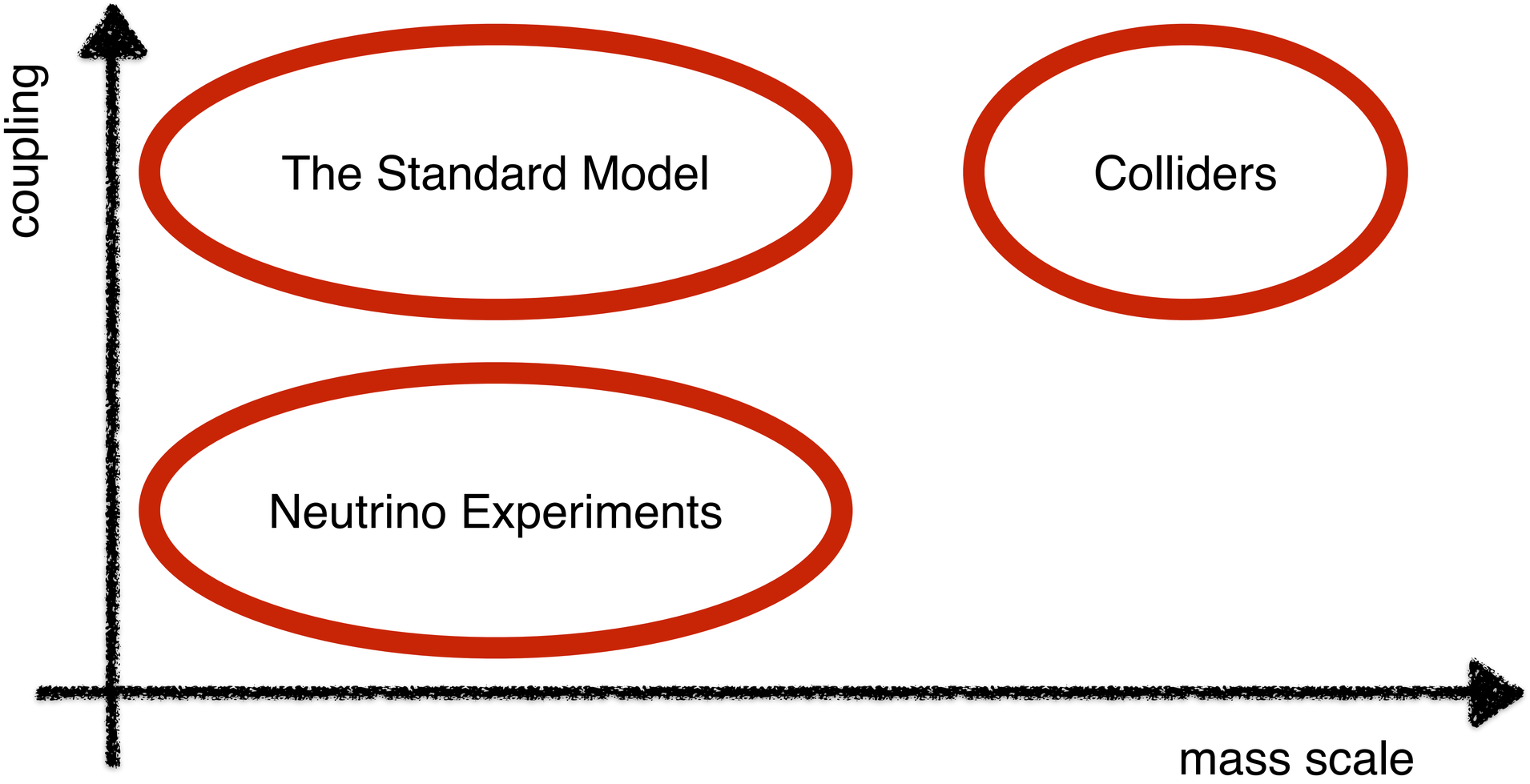

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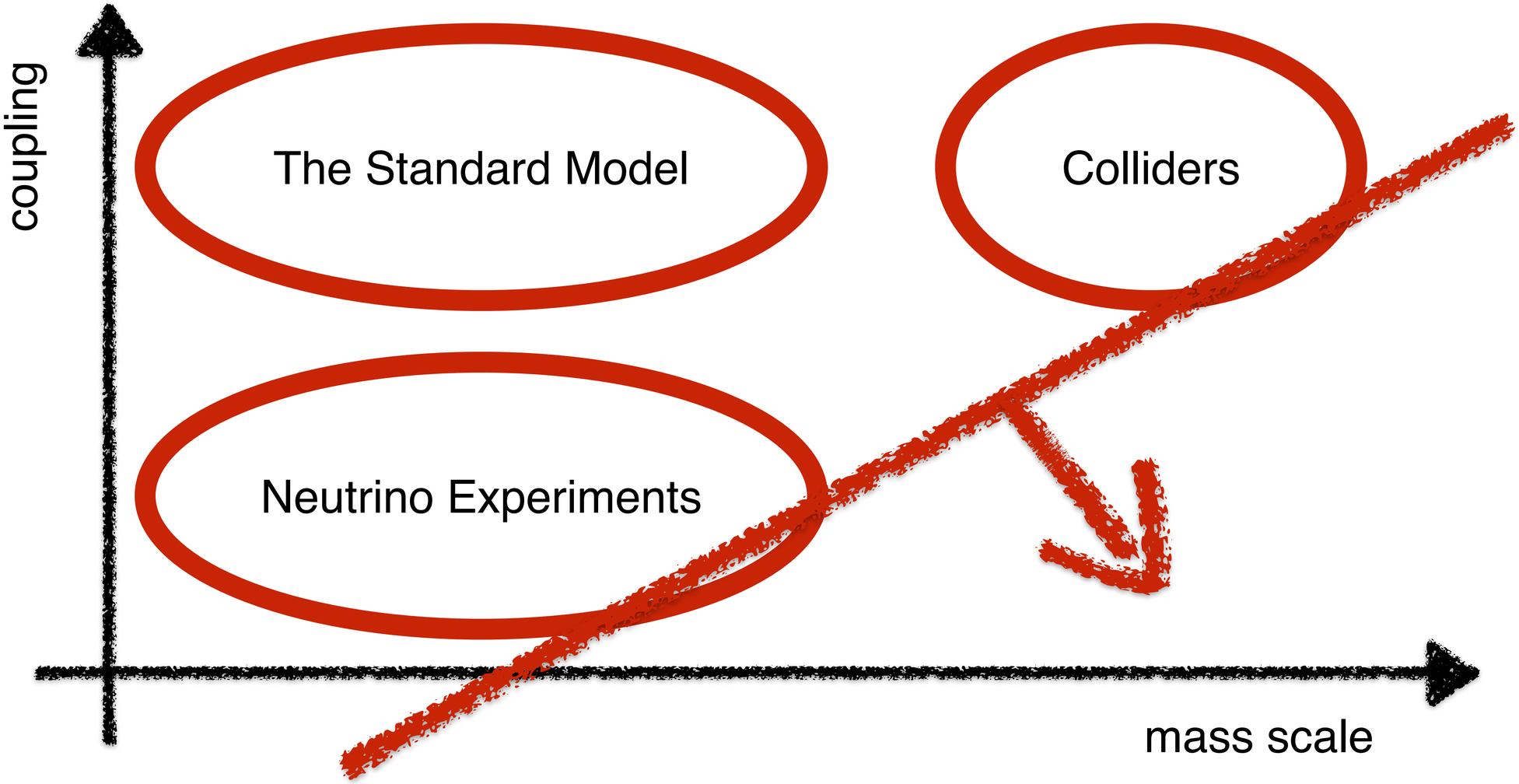

+ cosmic frontier experiments

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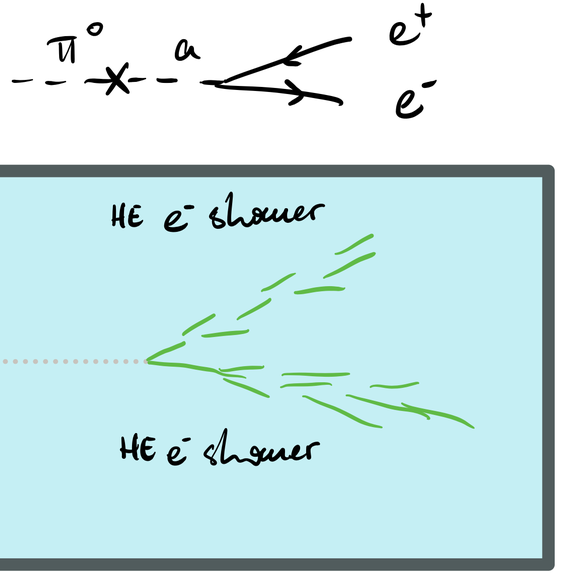
Near detector physics

Neutrino detectors are made to detect weakly coupled physics, including neutrinos.

There is a variety of physics that can be probed in near detectors,
such as the DUNE-ND or the Short Baseline Program, Palamara's talk
which could help us answer the outstanding questions of the standard model.

Light dark matter	Nature of dark matter
Axions	Strong CP, existence of PNGBs
Heavy neutral leptons	Mechanism of neutrino masses
Millicharged particles	Quantization of charge
Neutrino tridents	Precision physics
Dark photons	Existence of dark sectors
Light scalars	Existence of dark sectors
…	…



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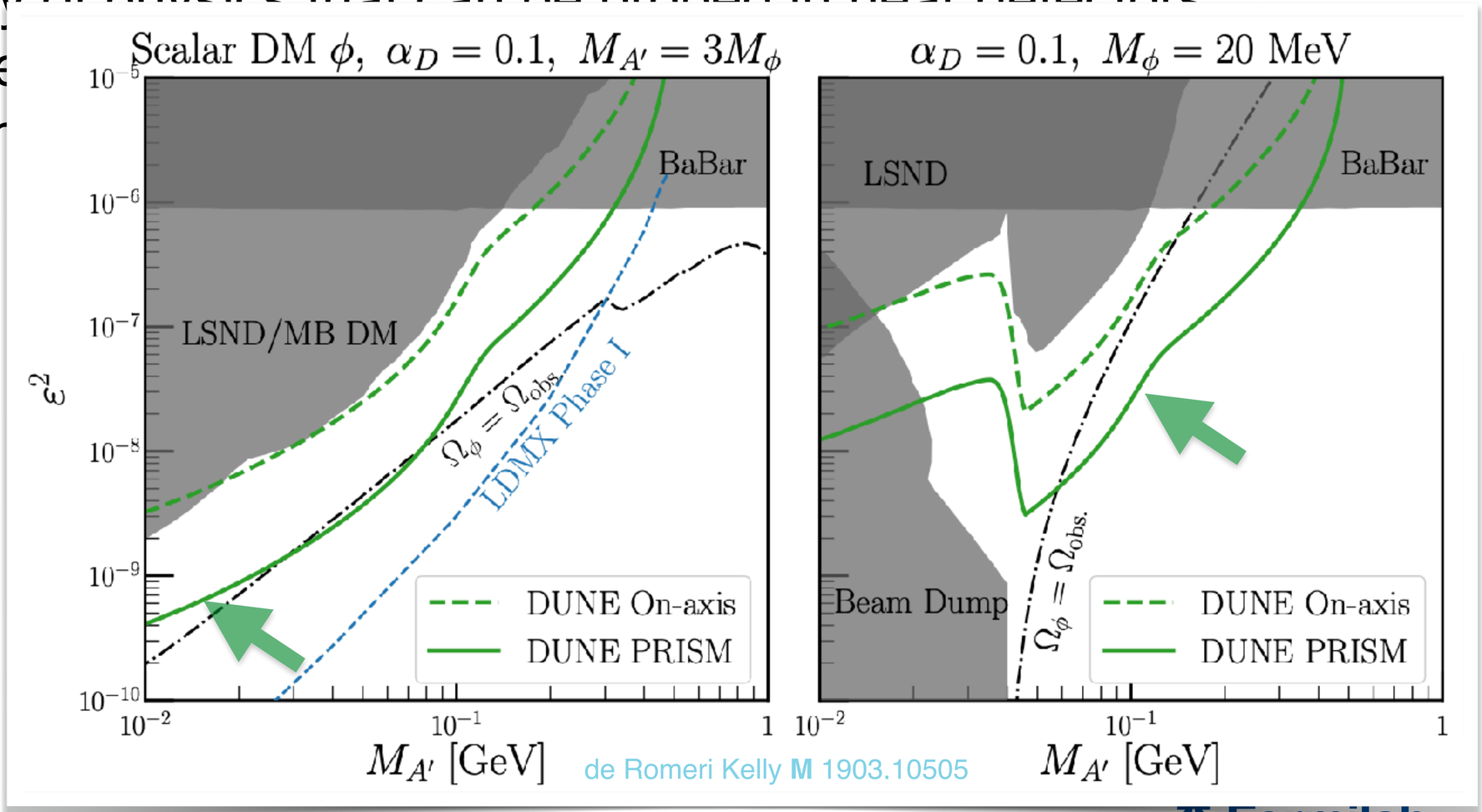

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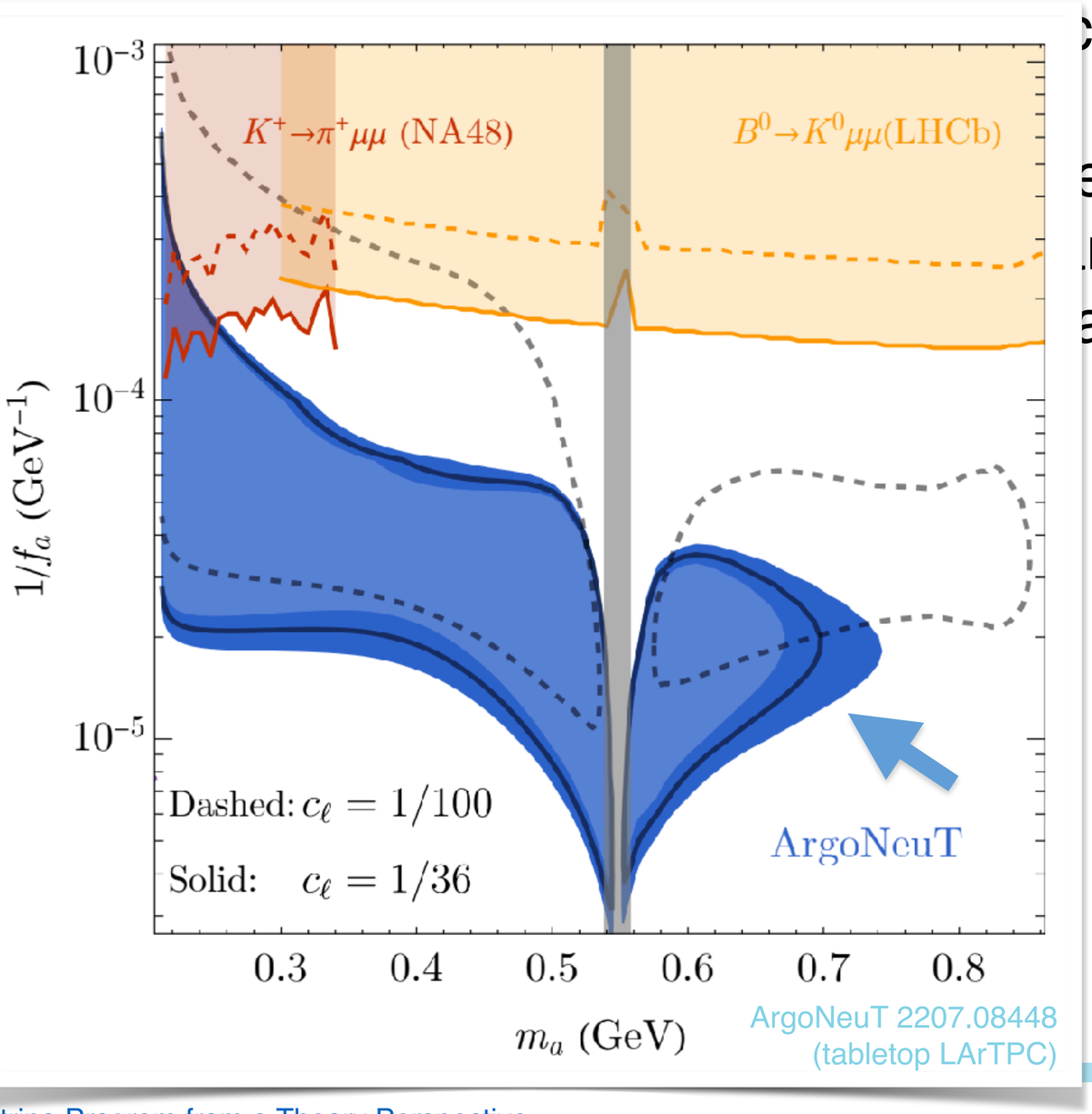

ArgoNeuT 2207.08448
(tabletop LArTPC)

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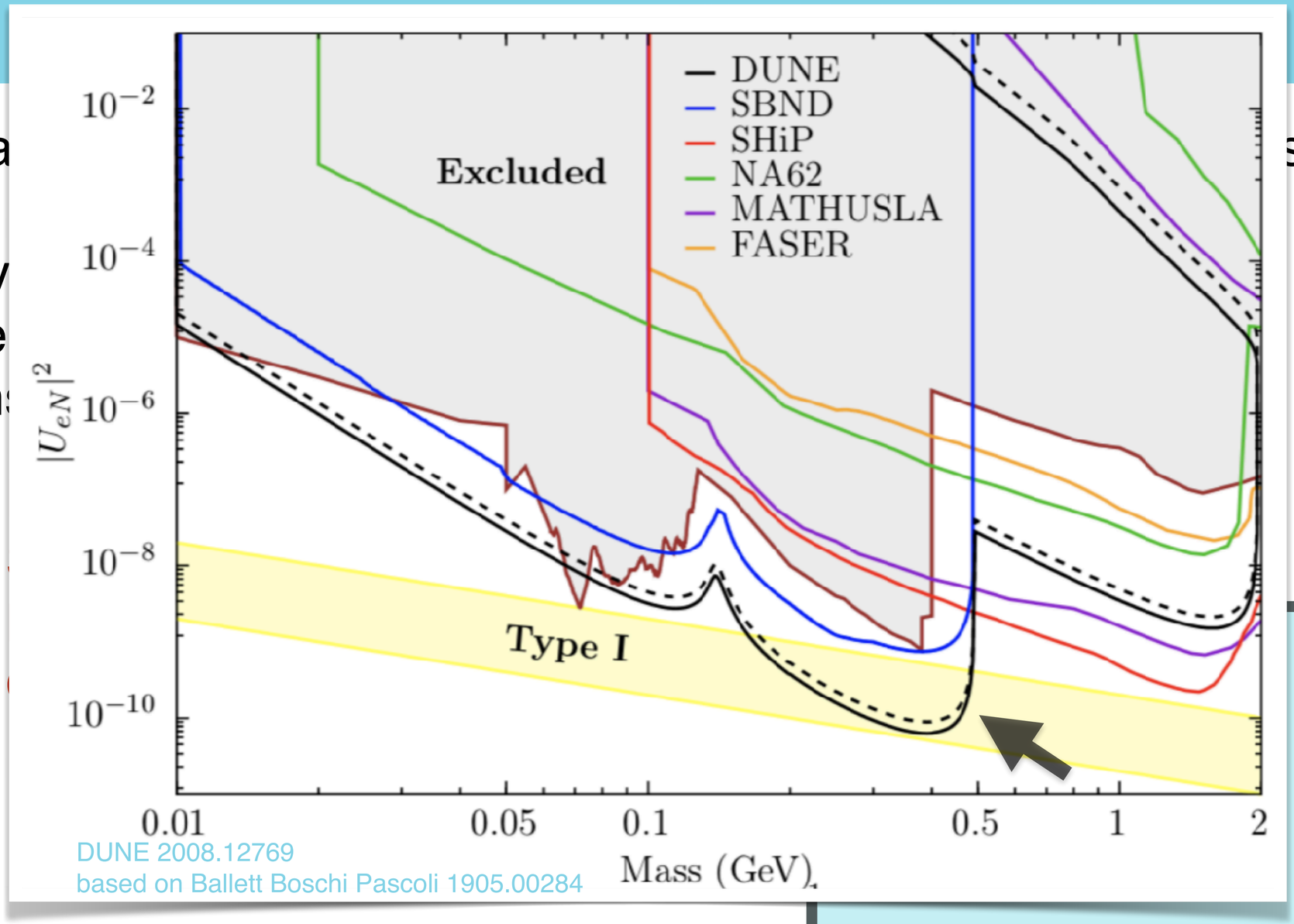

DUNE 2008.12769
based on Ballett Boschi Pascoli 1905.00284

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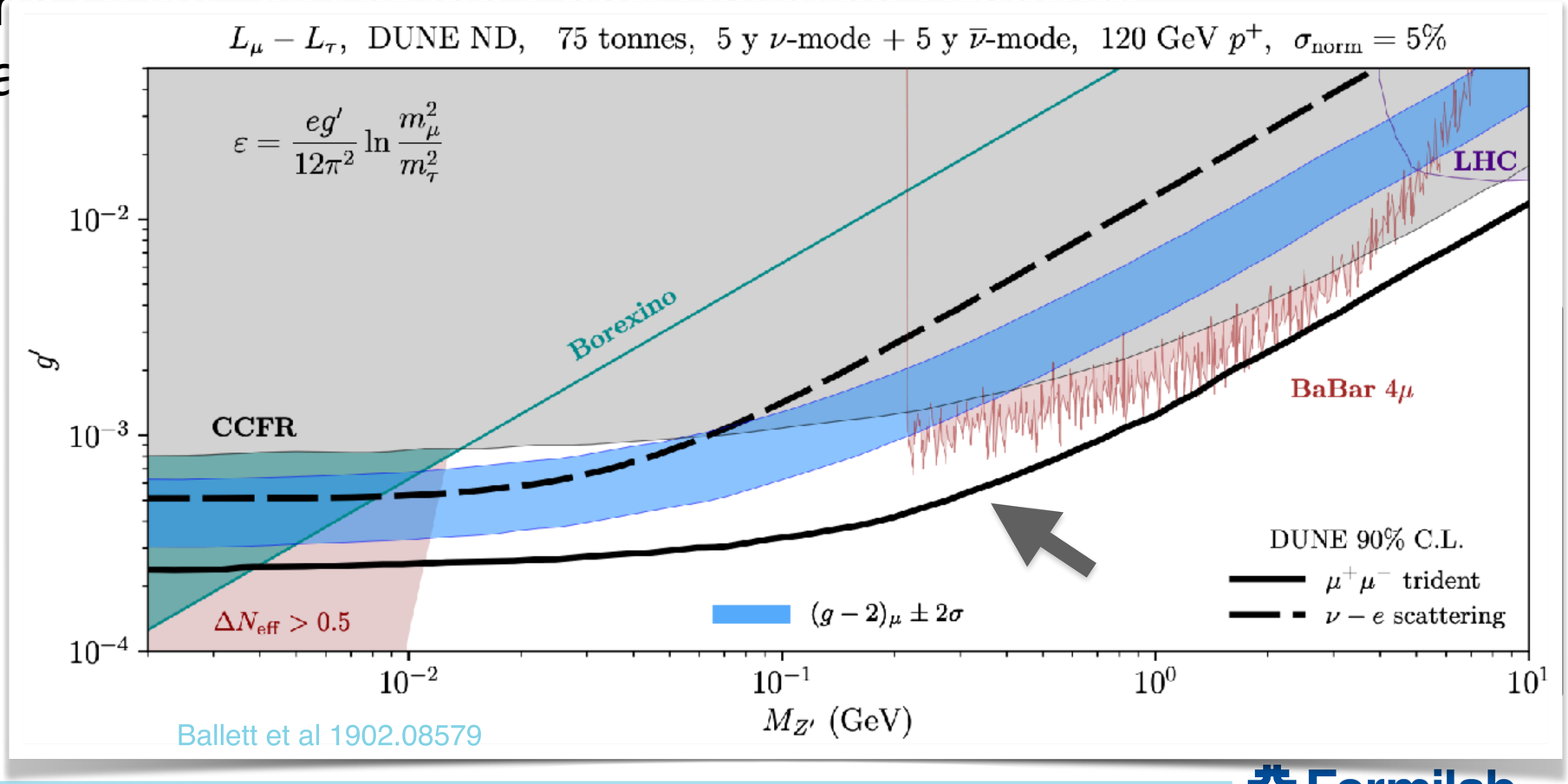

Ballett et al 1902.08579

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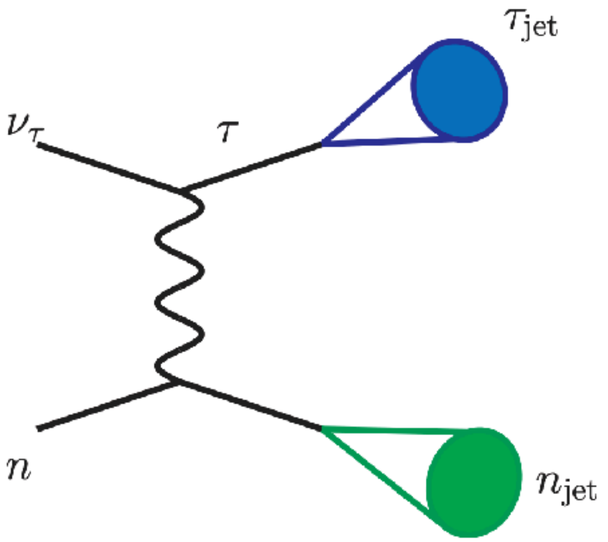
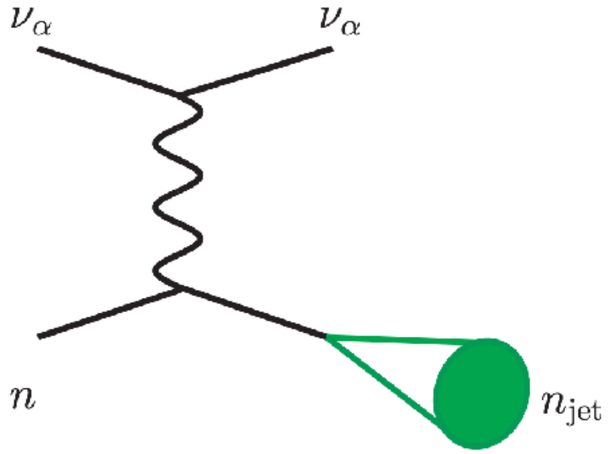
Far detector physics

Far detectors on the other hand are gigantic, but far from the beam.
The weakly coupled physics they probe is either non-beam related or neutrino-related

p^+ decay and n-nbar osc.	Unification of forces
Supernova dynamics	Astrophysics in extreme environments
Ultralight scalar fields	Dark matter
New interactions	Neutrino portal to new physics
Precision neutrino physics	Consistency of the standard model
…	…





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Far detectors on the
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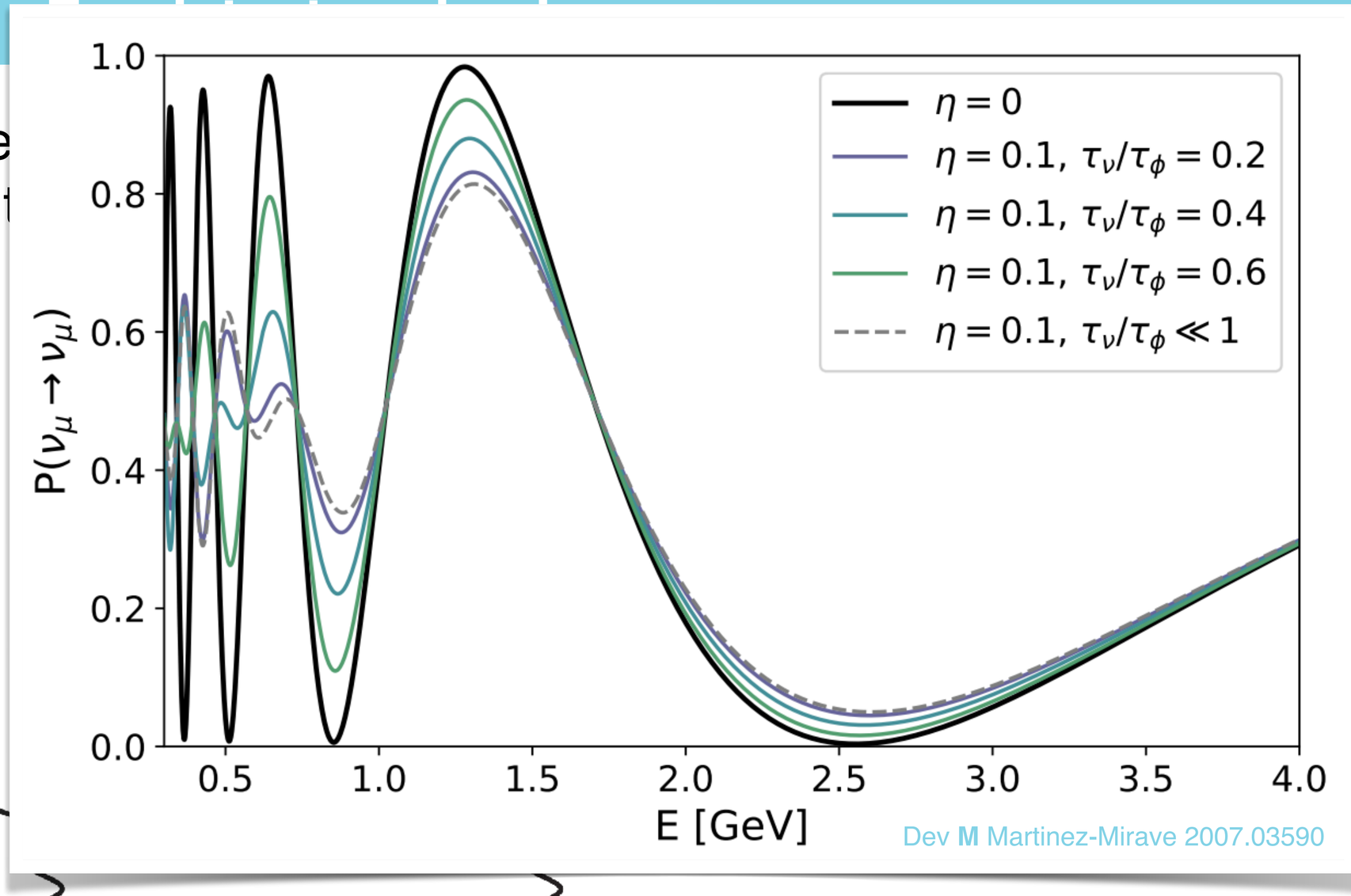
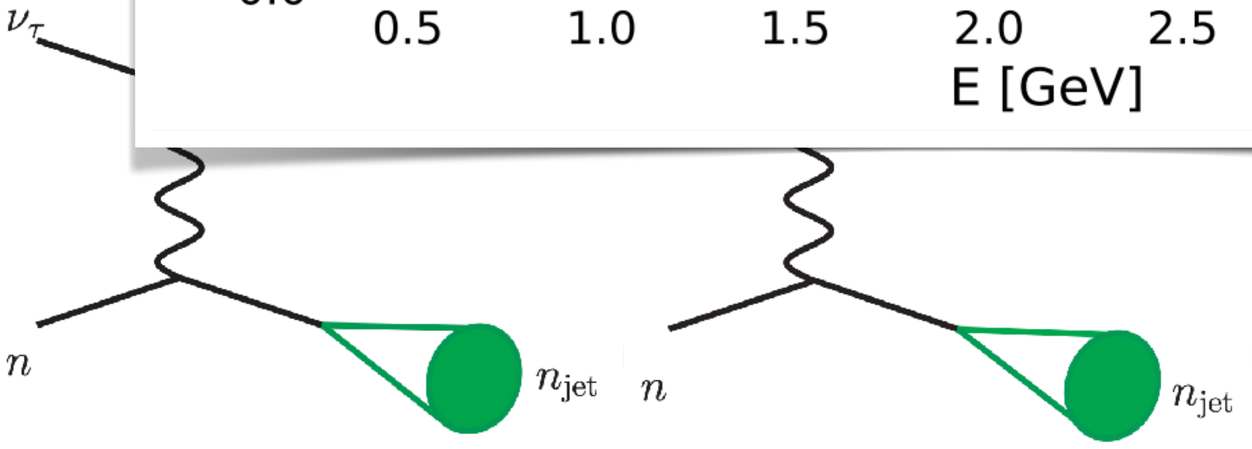


Dev **M** Martinez-Mirave 2007.03590



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Far detector physics

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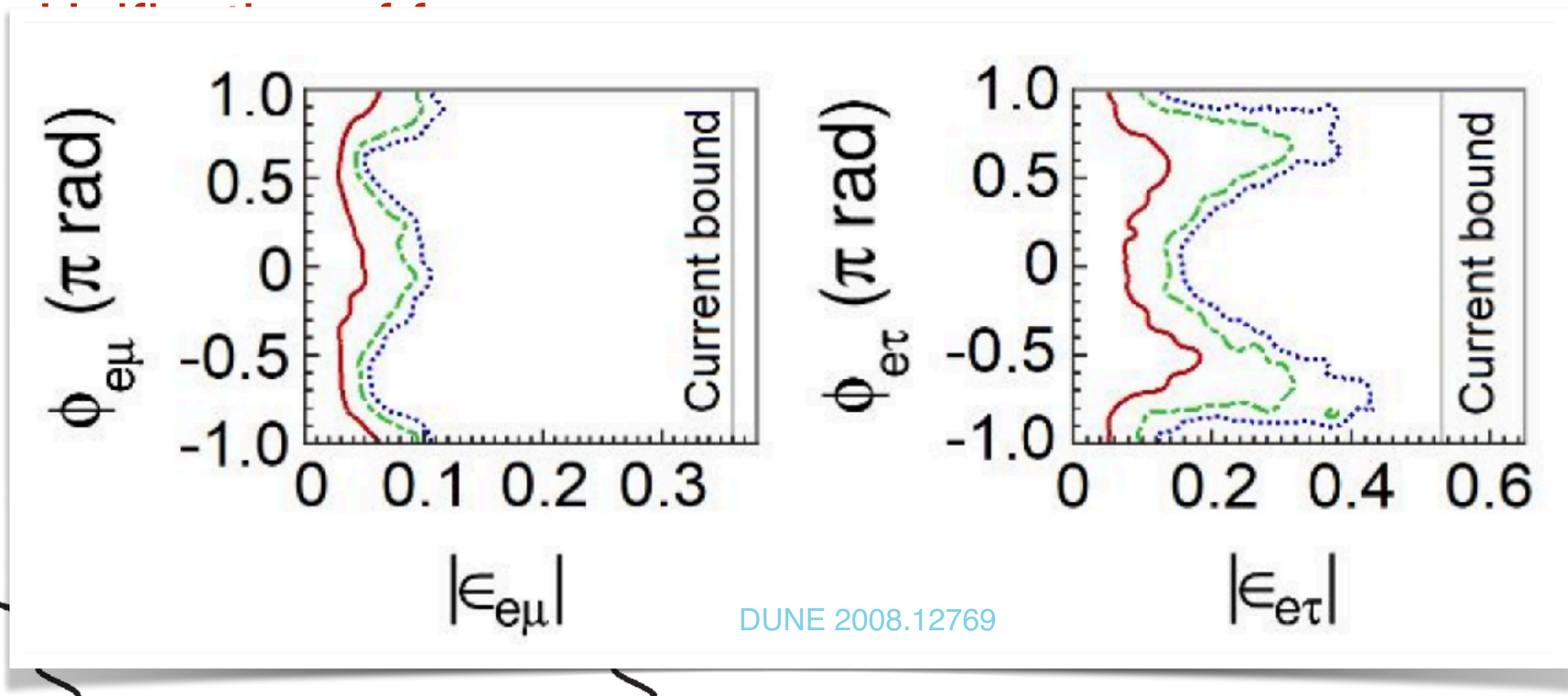
The weakly coupled physics they probe is either non-beam related or neutrino-related

- p^+ decay and n-nbar osc.
- Supernova dynamics
- Ultralight scalar fields
- **New interactions**
- Precision neutrino physics
- …



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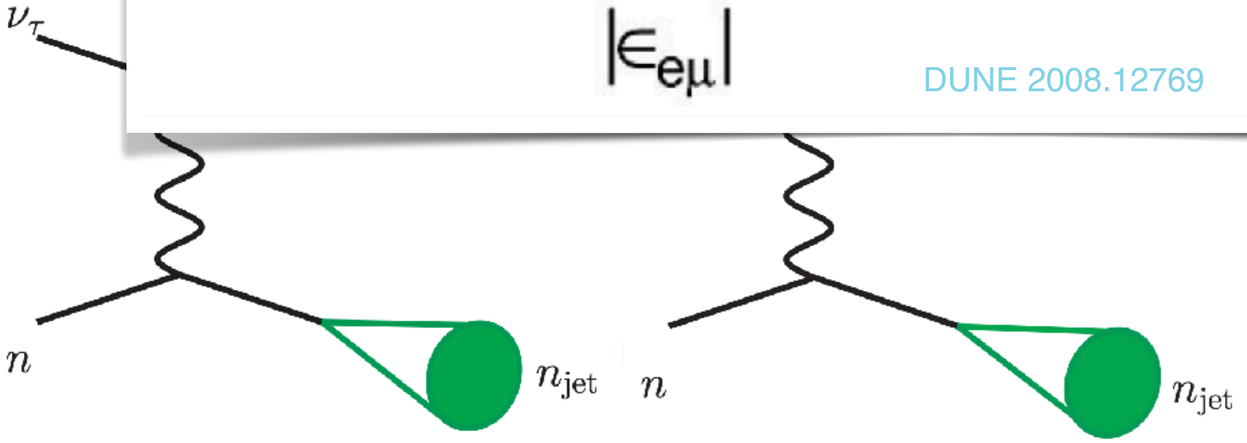

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Far detector physics

Far detectors on the [illegible] he beam.
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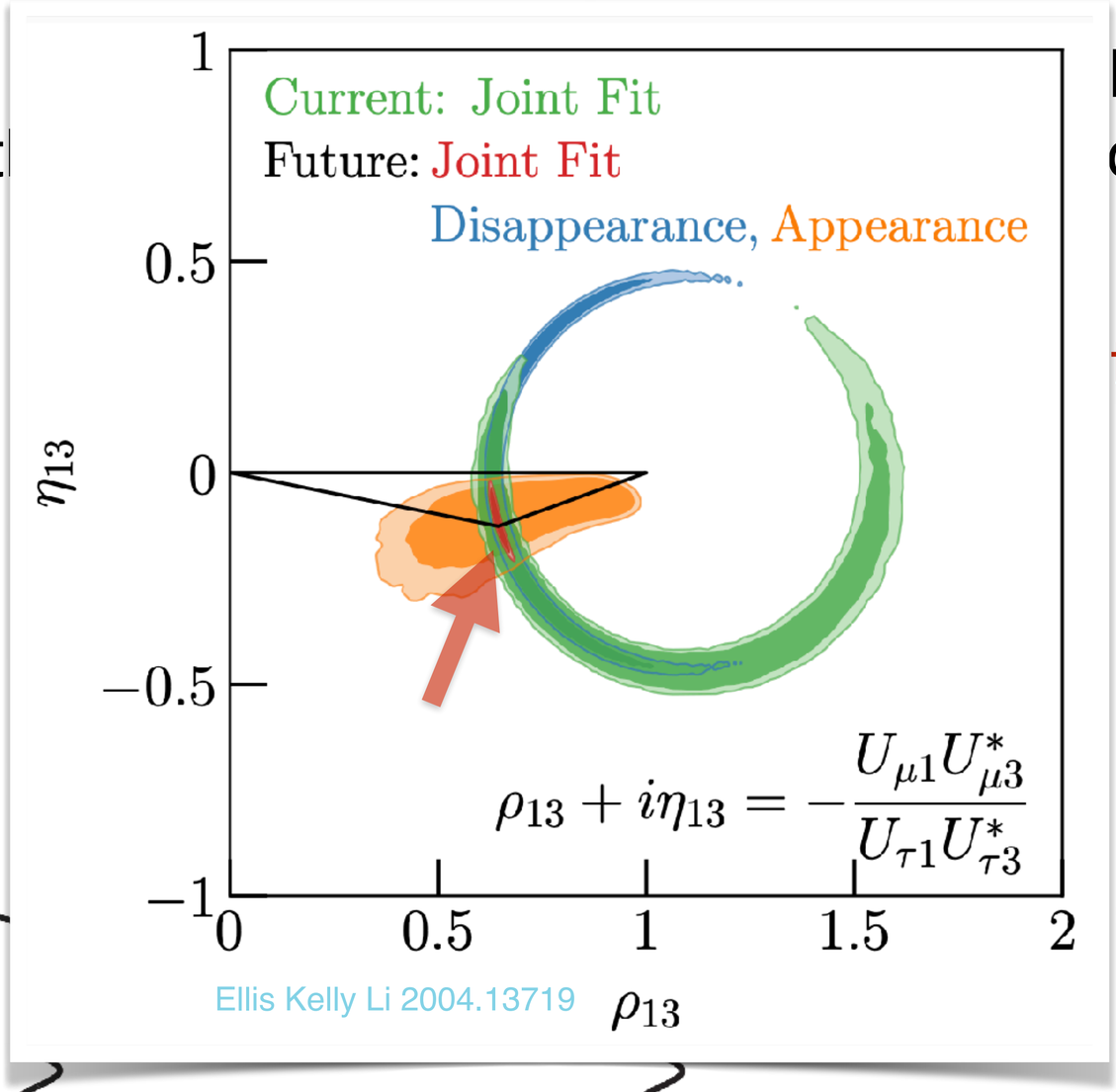
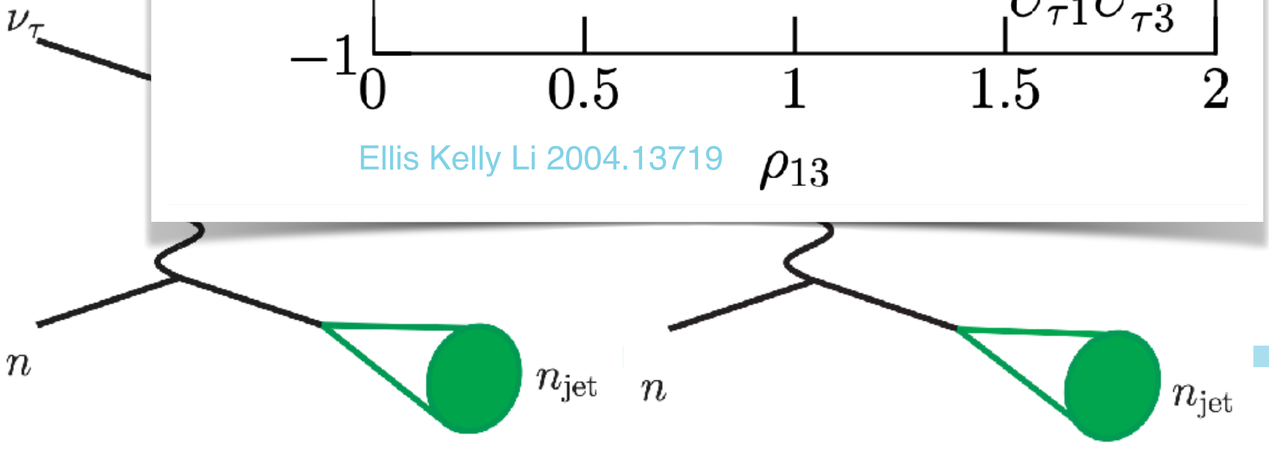


Ellis Kelly Li 2004.13719



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Besides DUNE…

Before concluding, let's take a bird's-eye view of the future program

Neutrinos need intensity, and intensity enables physics beyond neutrinos

The future beam upgrade at FNAL, besides providing the necessary intensity for the DUNE physics program, could also enable novel capabilities: dark sector searches with beam dumps; lepton flavor violation measurements; muon experiments; …

The **A**ccelerator **C**omplex **E**volution (**ACE**) upgrade will bring us the DUNE program in its full glory together with a comprehensive intensity frontier program

Valishev's talk

*See *Physics Opportunities for the Fermilab Booster Replacement* 2203.03925 for more details

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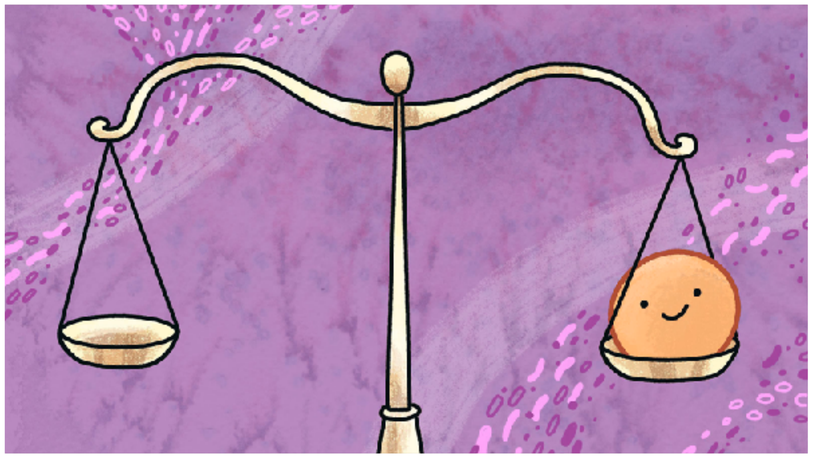
Conclusions

We do not know where new physics is

But we know that there needs to be new physics that address the outstanding questions of the standard model, in particular the mechanism of neutrino mass generation

Neutrino experiments are multipurpose experiments
neutrino experiments >> neutrinos

A vibrant neutrino program would allow for a precision neutrino physics program, scrutinizing the least known sector of the standard model, with broad BSM discovery potential, particularly geared towards weakly interacting new physics, complementary to EF, IF, and CF experiments



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